台灣農業研究 (J. Taiwan Agric. Res.) 62(4):321–339 (2013)
DOI: 10.6156/JTAR/2013.06204.03

Changes of Climatic Variables during Grain-filling Stage Affect Yield and Quality of Rice Cultivars Bred from Different Regions in Taiwan

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Abstract

Ho, C. H., C. M. Yang, C. L. Hsiao, and M. H. Lai. 2013. Changes of climatic variables during grain-filling stage affect yield and quality of rice cultivars bred from different regions in Taiwan. J. Taiwan Agric. Res. 62(4):321–339.

Changes in climatic variables during grain-filling stage are known to affect yield and quality of rice at harvest. However, there exist differential effects on cultivars that bred from varied regions with diversified genetic contexts and environmental conditions. To effectively response to different conditions emerging from changing climate for a stable food supply, it is necessary to further clarify the underlying mechanisms of climatic effects. This study was conducted in years from 2008 to 2010 with a total of 29 cropping seasons based on 24 Solar Terms calendar. Four rice (*Oryza sativa* L.) cultivars bred from different regions in Taiwan were selected for experiments, and weather data recorded from nearby meteorological station were used for analyses. The mean values of daily mean air temperature, daily maximum air temperature, daily minimum air temperature, day-night temperature difference, daily sunshine hours and daily irradiance during grain-filling stage were calculated as six climatic variables of MDMAT, MDMAXAT, MDMINAT, MDNTD, MDSH and MDIR, respectively. Results showed that temperature variables had a greater weight than irradiance and sunshine hour, and amylose, transparency and head rice rate of milled grains were the quality traits affected by temperature changes. The curvilinear relationships were significant only for 'TY4' in the first-half years (FHY), but were significant for all cultivars in the second-half years (SHY). Temperature variables also had an effect on grain yield, the convex curve patterns indicating that there were optimal temperature regimes. Analyses on the pooled data of 4 cultivars indicated that rice yields reached the plateau at MDMINAT of 23℃, MDMAT of 26.5℃ and MDMAXAT of 31℃ in FHY, and were at MDMINAT of 20℃, MDMAT of 24℃ and MDMAXAT of 29℃ in SHY. Both MDNTD and MDIR had a quadratic relationship with quality traits in SHY, and similar relationship was found in MDNTD with grain yield in SHY. This study demonstrated the differential effects of climatic variables during grain-filling stage on chemical components, physical characters and yield of rice grains in cultivars bred from varied regions. Temperature variables above the threshold values that obtained the maximum yield result in a decline of yield production.

Key words: Grain-filling stage, Climatic variable, Cultivar bred from varied regions, Rice quality, Rice yield.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the major food crops cultivated worldwide including Taiwan. As a traditional staple food, its cultivation hectarage reached 260,000 ha with a total of 1.37 million ton in 2012 (COA 2012). The

Received: August 26, 2013; Accepted: November 7, 2013.
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subtropical climate plus sufficient technical support enable a two-crop production system to ensure an abundant food supply for local demand. However, climate scenarios are quite opposite in these two crops. An increasing air temperature and solar radiation occurs in the first cropping season, while an inverse situation take place in the second cropping season making a differential outcome of climatic effects on yield and quality (Chu & Lu 1984; Liu *et al*. 1984). During grain-filling stage of first crop, rice plants often suffered high temperature impairments to result a high ratio of chalky grains; whereas, long period hot weather in tillering stage of second crop frequently reduce effective tillers. The low irradiance and sunshine hours during the late grain filling also limit the supplement of assimilates from photosynthesis, thereby restricting capacity of grain filling and thus lowering down rice yield of second crop by 20–25% relative to first crop (Lin & Hung 1979; Lin *et al*. 1979; Liu & Hsieh 1984; Lur *et al*. 2009).

Four aspects are mostly concerned in terms of rice quality, i.e., milling characteristics, grain appearance, nutritional value and cooking performance. Each part contributes to taste and eating nature of rice. For grain appearance, generally shape, uniformity, transparency and chalkiness (or whiteness) of grains are four important physical characters being taken into account. As for nutritional value, protein, fatty acids, starch, vitamins, minerals and water are the most interested chemical components (Kim *et al*. 1994; Hong *et al*. 2000; Hsu *et al*. 2000; Choi 2002). In addition to cultivational practices taken along the growing process, such as fertigation, irrigation and pests management, yield and qualiy of a rice crop are influenced by varietal genetic variability and environmental variation. Among environmental factors, temperature and radiatoin have been studied extensively (Tsai *et al*. 1984; Islam & Morison 1992; Lee *et al*. 2009; Ho *et al*. 2012). As literature indicated, high temperatures stimulate grain-filling rate and shorten grain-filling period to increase protein content and chalky grains but decrease amylose and grain weight, as well as to enhance respiration consumption at night and bring about reduced pollen germination percentage and sterility of spikelets (Zakaria *et al*. 2002; Hirai *et al*. 2003; Morita *et al*. 2004; Yamakawa *et al*. 2007; Mohammed & Tarpley 2010; Kim *et al*. 2011). Low temperatures occur during grain-filling would raise proportions of immature, green, abnormal and dead grains and contents of crude protein and amylose in endosperm of rice grains (Huang & Lur 2000; Ahmed *et al*. 2008). As a result, temperatures higher than 30℃ or lower than 20℃ would not only reduce milling quality, appearance and yield of rice grains but also lessen their nutritional value, eating and cooking performance. Some experimental results further revealed that 1℃ increase at night would cut down 10% yield at harvest (Kukla & Karl 1993; Easterling *et al*. 1997; Peng *et al*. 2004), which became more evident when rate of temperature increase was greater at night than in daytime.

Daily irradiance and sunshine hours also play a role in affecting rice yield and quality. Nagarajan *et al*. (2010) pointed out that there were positive relationships between irradiance and spikelet fertility, 1000-grain weight, harvest index and production of rice. Yang (1994) reported that under well-watered condition, grain yield of rice increased with the increasing cumulative daily irradiance and daily mean air temperature. Others (Tsai *et al*. 1984; Lur *et al*. 2006) showed that photosynthetic rate was inhibited at low irradiance so that grain-filling was jeopardized to cause lower grain-filling rate and 1000-grain weight.

The 2007 IPCC Fourth Assessment Report on climate change disclosed an increasing trend of air temperature in the future (IPCC 2007). To safeguard a stable and available food supply system, it is necessary to continue vigorous efforts of research against negative impacts emerging from a changing climate. Although changes in climatic variables during grain-filling stage of rice have been known to affect yield and quality, the differential effects on cultivars that bred from varied regions with diversified genetic contexts and environmental conditions are less explored. To be effectively response to different conditions rising from rapid climate change, the underlying mechanisms of climatic effects should be studied in more detail. The present research was carried out for the objectives as aforementioned.

MATERIALS AND METHODS

Cropping Seasons and Cultivation

Field experiments were conducted at the experimental farm of Taiwan Agricultural Research Institute (TARI; Wufeng, Taichung) in years from 2008 to 2010 with a total of 29 cropping seasons. Three-to-four-leaf stage rice seedlings were machined transplanted in a north-south direction based on 24 Solar Terms calendar, with the terms separated by 15 days apart along traditional East Asian lunisolar calendars. In the first-half year (seasons of First Crop), rice was planted 5 times (5 cropping seasons) taking solar term 'Lichun' (literally "start of spring" or "the first day of spring") as the center cropping season, and another 5 plantings adopted solar term 'Dashu' (literally "major heat" or "first day of mid-summer") as the center season in the second-half year (seasons of Second Crop) (Tables 1A and 1B). Rice cultivars, namely, 'TY4', 'TNG71', 'TK9' and 'KH145', bred from different regions in Taiwan were selected for experiments (Table 2), and weather data recorded from nearby agricultural meteorological station at TARI were used for analyses.

As shown in Table 2, these 4 selected rice cultivars were bred by different research institutions, located from the northern to the southern part of Taiwan, with diverse characteristics set by breeders. Similar management practices were applied to each cultivar in every cropping season so that growth and development of rice plants were mainly attributed to variation of climatic conditions for each cultivar. Multiple seedlings per hill were machine-transplanted in every cropping season, with a plot size of 0.1 ha (50 m × 20 m) for each cultivar that distributed randomly along the field. The soil pH was 5.36 and organic matter was 2.21%. The basal dose of fertilizer (Tai-Fei No.39, N : P : K = 12 : 18 : 12, granule, Taiwan Fertilizer Company, Kaohsiung, Taiwan) was applied at a rate of 200 kg ha^{-1} at 2–3 days before transplanting, followed by application of ammonium sulfate (21% N, granule, TFC, Kaohsiung, Taiwan) at a rate of 200 kg ha^{-1} at 1–2 weeks after transplanting (WAT). On 4–5 WAT, ammonium sulfate of 200 kg ha^{-1} was applied and Tai-Fei No.39 of 100 kg ha^{-1} was used at 1–2 weeks before heading as last dose. The herbicide 'Butachlor + Benthiocarb' (8% granule, 2.4 kg a.i ha^{-1}, Taiwan Ihara Chemical Co. Ltd., Taipei) was sprayed to control annual weeds upon transplanting and hand weeding was practiced 3–4 WAT. The Camellia sp. oil cake was sprayed over fields 1–2 times to control apple snails at a rate of 100 kg ha^{-1}, while 3% validamycin A (soluble concentrate, 0.036 L a.i. ha^{-1}, 1000×, Rich Country Chemical Corp., Taoyuan, Taiwan) and 10% Tecloftalam (wettable powder, 0.1 kg a.i. ha^{-1}, 1000×, Sinon Chemical Co., Ltd., Taichung, Taiwan) were applied to control sheath blight and bacterial

leaf blight, respectively. The 6% Cartap hydrochloride (granule, 1.8 kg a.i. ha^{-1}, Sinon Chemical Co., Ltd., Taichung, Taiwan) was applied when symptoms caused by rice leaf folder and stem borer occurred. For other pests, 40.64% Carbofuran (suspension concentrates, 0.49 L a.i. ha^{-1}, 1000×, Chia Yi Chemical Industry Co., Ltd., Tainan, Taiwan) was used.

Climatic Variables

A meteorological station designated for agricultural use and operated by TARI is situated within 500 meters away from the experimental fields. The mean values of daily mean air temperature (DMAT), daily maximum air temperature (DMAXAT), daily minimum air temperature (DMINAT), day-night temperature difference (DNTD), daily sunshine hours (DSH) and daily irradiance (DIR) during grain-filling stage were calculated to obtained the corresponding six climatic variables of MDMAT, MDMAXAT, MDMINAT, MDNTD, MDSH and MDIR, respectively. The regression analyses were performed to link and compare the differential effects of climatic variables on quality traits and grain yield.

Rice Quality Analysis (Physical Characters and Chemical Components)

At maturity of every cropping season, an area of 10 m^2 was harvested, with three replicates for each cultivar and the averaged value was used as representative for yield determination. After fresh weights taken and oven-dried at 40℃ for more than 72 h, dry weights were recorded at grain water content around 12–13% to estimate yields (Mg ha^{-1}) and analyze quality traits (Hsiao *et al*. 2009). Forty grains were randomly selected from each replication and viewed by a 5-fold enlarger (Model 66-SII, LPL Co. Ltd., Japan) to measure length and width of grains, and grain thickness was determined by a dial thickness gauge (Model SM540, TECLOCK Co., Japan). One thousand grain were also randomly selected to classify the proportions of dead, head and non-head rice by a grain color sorter (Model RGQI20A, Satake Co., Japan); the non-head rice included immature, damaged, chalky, green, discolored and cracked grains. The brightness of grains, in terms of transparency and whiteness, were determined by a milling meter (Model MM1C, Satake Co., Japan). The chemical components were analyzed by a near infrared grain tester (Model AN-820, Kett Co., Japan) to determine crude protein and amylose of milled grains and crude protein, amylose and free fatty acids of brown rice using the internal calibration curves for japonica rice.

Data Analysis and Statistics

The statistics of experimental data were conducted by the Statistical Analysis System (SAS version 9.1), while graphs were plotted by using the SigmaPlot software (version 10.0).

RESULTS AND DISCUSSION

To further understand how changes of climatic variables during grain-filling stage affect yield and quality of rice cultivars bred from different regions in Taiwan, this study adopted 24 Solar Terms calendar to plant rice and obtained sets of weather data from 29 cropping seasons in a 3-year experimental period. Based on the planting calendar and growth development (Tables 1 and 2), three climatic variables (i.e., MDMINAT, MDMAT and MDMAXAT) calculated from the data collected from the nearby weather station, for every cropping season and each rice cultivar, were found correlated with quality traits, while the other three variables had a less weight on the correlations (data not shown). Among them, changes in amylose and transparency of milled rice and head

Table 1A. Dates of transplanting (DT), heading (DHe) and harvest (DHa) and days required from heading to harvest of 29 cropping seasons for rice cultivar 'TY4' and 'TNG71' grown in 2008–2010.

Cropping season	DT	DHe	DHa	Cropping season	DT	DHe	DHa
TY4, 1st crop, 2008				2nd crop, 2008			
SS – 30[z]	na[y]	na	na	MH – 30	06/19/2008	08/21/2008	10/12/2008 (53)
SS – 15	01/16/2008	04/24/2008	06/09/2008 (47[x])	MH – 15	07/08/2008	09/01/2008	10/21/2008 (51)
SS	02/04/2008	05/02/2008	06/15/2008 (41)	MH	07/23/2008	09/16/2008	11/03/2008 (49)
SS + 15	02/19/2008	05/07/2008	06/19/2008 (44)	MH + 15	08/06/2008	09/28/2008	11/11/2008 (45)
SS + 30	03/06/2008	05/11/2008	06/23/2008 (44)	MH + 30	08/21/2008	10/14/2008	12/10/2008 (58)
1st crop, 2009				2nd crop, 2009			
SS – 30	12/24/2008	04/03/2009	05/21/2009 (49)	MH – 30	06/23/2009	08/20/2009	10/19/2009 (61)
SS – 15	01/20/2009	04/14/2009	05/30/2009 (47)	MH – 15	07/07/2009	08/30/2009	10/25/2009 (57)
SS	02/09/2009	04/27/2009	06/10/2009 (45)	MH	07/23/2009	09/17/2009	11/01/2009 (46)
SS + 15	02/19/2009	05/07/2009	06/18/2009 (43)	MH + 15	08/10/2009	09/29/2009	11/16/2009 (49)
SS + 30	03/05/2009	05/17/2009	06/25/2009 (40)	MH + 30	08/20/2009	10/12/2009	11/29/2009 (49)
1st crop, 2010				2nd crop, 2010			
SS – 30	12/31/2009	04/02/2010	05/17/2010 (46)	MH – 30	06/22/2010	08/15/2010	10/11/2010 (58)
SS – 15	01/14/2010	04/14/2010	05/25/2010 (42)	MH – 15	07/07/2010	09/06/2010	10/24/2010 (49)
SS	02/04/2010	04/21/2010	05/30/2010 (40)	MH	07/23/2010	09/15/2010	10/26/2010 (42)
SS + 15	02/23/2010	05/05/2010	06/17/2010 (44)	MH + 15	08/05/2010	09/29/2010	11/14/2010 (47)
SS + 30	03/04/2010	05/11/2010	06/22/2010 (43)	MH + 30	08/25/2010	10/15/2010	12/07/2010 (54)

Table 1A. Dates of transplanting (DT), heading (DHe) and harvest (DHa) and days required from heading to harvest of 29 cropping seasons for rice cultivar 'TY4' and 'TNG71' grown in 2008–2010. (continued)

Cropping season	DT	DHe	DHa	Cropping season	DT	DHe	DHa
TNG71, 1st crop, 2008				2nd crop, 2008			
SS – 30	na	na	na	MH – 30	06/19/2008	08/18/2008	10/07/2008 (51)
SS – 15	01/16/2008	04/21/2008	06/03/2008 (44)	MH – 15	07/08/2008	09/02/2008	10/21/2008 (50)
SS	02/04/2008	04/24/2008	06/05/2008 (43)	MH	07/23/2008	09/17/2008	11/03/2008 (48)
SS + 15	02/19/2008	05/06/2008	06/11/2008 (37)	MH + 15	08/06/2008	09/26/2008	11/10/2008 (46)
SS + 30	03/06/2008	05/08/2008	06/18/2008 (42)	MH + 30	08/21/2008	10/13/2008	12/03/2008 (52)
1st crop, 2009				2nd crop, 2009			
SS – 30	12/24/2008	04/06/2009	05/20/2009 (45)	MH – 30	06/23/2009	08/17/2009	10/12/2009 (57)
SS – 15	01/20/2009	04/17/2009	06/03/2009 (48)	MH – 15	07/07/2009	08/28/2009	10/22/2009 (56)
SS	02/09/2009	04/23/2009	06/09/2009 (48)	MH	07/23/2009	09/15/2009	10/29/2009 (45)
SS + 15	02/19/2009	05/05/2009	06/14/2009 (41)	MH + 15	08/10/2009	09/27/2009	11/12/2009 (47)
SS + 30	03/05/2009	05/14/2009	06/23/2009 (41)	MH + 30	08/20/2009	10/07/2009	11/18/2009 (43)
1st crop, 2010				2nd crop, 2010			
SS – 30	12/31/2009	03/31/2010	05/11/2010 (46)	MH – 30	06/22/2010	08/14/2010	10/10/2010 (58)
SS – 15	01/14/2010	04/12/2010	05/24/2010 (42)	MH – 15	07/07/2010	08/30/2010	10/20/2010 (52)
SS	02/04/2010	04/20/2010	05/26/2010 (40)	MH	07/23/2010	09/12/2010	10/20/2010 (39)
SS + 15	02/23/2010	05/02/2010	06/07/2010 (44)	MH + 15	08/05/2010	09/22/2010	11/07/2010 (47)
SS + 30	03/04/2010	05/09/2010	06/16/2010 (43)	MH + 30	08/25/2010	10/12/2010	12/01/2010 (51)

[z] SS: 'Lichun' (literally "start of spring" or "the first day of spring"). SS - 30 and SS - 15 are transplanting of rice seedlings at 30 and 15 days before 'Lichun'; SS + 15 and SS + 30 are 15 and 30 days after the date of 'Lichun'. MH: 'Dashu' (literally "major heat" or "first day of mid-summer"). MH – 30 and MH – 15 are transplanting of rice seedlings at 30 and 15 days before 'Dashu'; MH + 15 and MH + 30 are 15 and 30 days after the date of 'Dashu'.

[x] numbers in parentheses are days required from heading to harvest.

[y] na: not available.

Table 1B. Dates of transplanting (DT), heading (DHe) and harvest (DHa) and days required from heading to harvest of 29 cropping seasons for rice cultivar 'TK9' and 'KH145' grown in 2008–2010.

Cropping season	DTy	DHe	DHa	Cropping season	DT	DHe	DHa
TK9, 1st crop, 2008				2nd crop, 2008			
SS – 30[z]	na[y]	na	na	MH – 30	06/19/2008	08/24/2008	10/14/2008 (52)
SS – 15	01/16/2008	04/27/2008	06/10/2008 (45[x])	MH – 15	07/08/2008	09/08/2008	10/28/2008 (51)
SS	02/04/2008	05/05/2008	06/16/2008 (39)	MH	07/23/2008	09/21/2008	11/09/2008 (50)
SS + 15	02/19/2008	05/12/2008	06/22/2008 (42)	MH + 15	08/06/2008	10/02/2008	11/18/2008 (48)
SS + 30	03/06/2008	05/13/2008	06/25/2008 (44)	MH + 30	08/21/2008	10/21/2008	12/16/2008 (57)
1st crop, 2009				2nd crop, 2009			
SS – 30	12/24/2008	04/17/2009	05/26/2009 (40)	MH – 30	06/23/2009	08/19/2009	10/21/2009 (64)
SS – 15	01/20/2009	04/22/2009	06/08/2009 (48)	MH – 15	07/07/2009	09/01/2009	10/29/2009 (59)
SS	02/09/2009	04/30/2009	06/11/2009 (43)	MH	07/23/2009	09/22/2009	11/05/2009 (45)
SS + 15	02/19/2009	05/08/2009	06/17/2009 (41)	MH + 15	08/10/2009	10/02/2009	11/22/2009 (52)
SS + 30	03/05/2009	05/18/2009	06/25/2009 (39)	MH + 30	08/20/2009	10/14/2009	12/06/2009 (54)
1st crop, 2010				2nd crop, 2010			
SS – 30	12/31/2009	04/08/2010	05/18/2010 (41)	MH – 30	06/22/2010	08/19/2010	10/12/2010 (55)
SS – 15	01/14/2010	04/09/2010	05/25/2010 (37)	MH – 15	07/07/2010	09/07/2010	10/25/2010 (49)
SS	02/04/2010	04/21/2010	05/31/2010 (41)	MH	07/23/2010	09/14/2010	11/01/2010 (49)
SS + 15	02/23/2010	05/06/2010	06/14/2010 (40)	MH + 15	08/05/2010	10/04/2010	11/21/2010 (49)
SS + 30	03/04/2010	05/10/2010	06/21/2010 (43)	MH + 30	08/25/2010	10/19/2010	12/15/2010 (58)

Table 1B. Dates of transplanting (DT), heading (DHe) and harvest (DHa) and days required from heading to harvest of 29 cropping seasons for rice cultivar 'TK9' and 'KH145' grown in 2008–2010. (continued)

Cropping season	DTy	DHe	DHa	Cropping season	DT	DHe	DHa
KH145, 1st crop, 2008				2nd crop, 2008			
SS – 30	na	na	na	MH – 30	06/19/2008	08/20/2008	10/08/2008 (50)
SS – 15	01/16/2008	04/24/2008	06/05/2008 (43)	MH – 15	07/08/2008	09/05/2008	10/26/2008 (52)
SS	02/04/2008	05/02/2008	06/11/2008 (37)	MH	07/23/2008	09/19/2008	11/06/2008 (49)
SS + 15	02/19/2008	05/07/2008	06/18/2008 (43)	MH + 15	08/06/2008	09/30/2008	11/11/2008 (43)
SS + 30	03/06/2008	05/10/2008	06/23/2008 (46)	MH + 30	08/21/2008	10/18/2008	12/14/2008 (58)
1st crop, 2009				2nd crop, 2009			
SS – 30	12/24/2008	04/05/2009	05/24/2009 (50)	MH – 30	06/23/2009	08/18/2009	10/18/2009 (64)
SS – 15	01/20/2009	04/16/2009	06/05/2009 (51)	MH – 15	07/07/2009	08/31/2009	10/27/2009 (59)
SS	02/09/2009	04/23/2009	06/09/2009 (48)	MH	07/23/2009	09/18/2009	11/03/2009 (45)
SS + 15	02/19/2009	05/05/2009	06/14/2009 (41)	MH + 15	08/10/2009	10/01/2009	11/15/2009 (52)
SS + 30	03/05/2009	05/15/2009	06/24/2009 (41)	MH + 30	08/20/2009	10/09/2009	11/26/2009 (54)
1st crop, 2010				2nd crop, 2010			
SS – 30	12/31/2009	04/06/2010	05/16/2010 (41)	MH – 30	06/22/2010	08/15/2010	10/11/2010 (58)
SS – 15	01/14/2010	04/17/2010	05/24/2010 (38)	MH – 15	07/07/2010	09/06/2010	10/21/2010 (46)
SS	02/04/2010	04/22/2010	05/27/2010 (36)	MH	07/23/2010	09/17/2010	10/31/2010 (45)
SS + 15	02/23/2010	05/05/2010	06/07/2010 (34)	MH + 15	08/05/2010	10/02/2010	11/18/2010 (48)
SS + 30	03/04/2010	05/11/2010	06/16/2010 (37)	MH + 30	08/25/2010	10/18/2010	12/12/2010 (56)

[z] SS: 'Lichun' (literally "start of spring" or "the first day of spring"). SS - 30 and SS - 15 are transplanting of rice seedlings at 30 and 15 days before 'Lichun'; SS + 15 and SS + 30 are 15 and 30 days after the date of 'Lichun'. MH: 'Dashu' (literally "major heat" or "first day of mid-summer"). MH – 30 and MH – 15 are transplanting of rice seedlings at 30 and 15 days before 'Dashu'; MH + 15 and MH + 30 are 15 and 30 days after the date of 'Dashu'.

[x] numbers in parentheses are days required from heading to harvest.

[y] na: not available.

Table 2. The information about rice (*Oryza sativa* L.) cultivars selected for this study.

Rice cultivar	Institution release	Characteristics	Coordinate
Taoyuan No. 4 (TY4)	Taoyuan District Agricultural Research and Extension Station	Good eating quality; resistant to lodging; low on-site sprouting rate; low threshing rate; resistant to leaf blast (Chen *et al*. 2007)	121.028595 °E 24.952262 °N
Tainung No. 71 (TNG71)	Taiwan Agricultural Research Institute	Aromatic rice; good grain transparency; low chalky grains; better viscosity and elasticity of cooked rice (Lai *et al*. 2001)	120.695524 °E 24.027955 °N
Taikeng No. 9 (TK9)	Taichung District Agricultural Research and Extension Station	Good grain uniformity; good grain transparency; good grain appearance; good plant type; resistant to lodging; resistant to silk leaf blight, spot planthopper and white-backed planthopper (Hsu & Sung 1993)	120.533848 °E 24.000872 °N
Kaohsiung No. 145 (KH145)	Kaohsiung District Agricultural Research and Extension Station	Good milling quality; good grain transparence; low grain white belly; low crude protein content; good plant type; suitable for both crops (Chiu & Wu 2005)	120.524276 °E 22.709576 °N

rice ratio to variations of climatic variables were plotted and their regression relations were analyzed (Figs. 1–3). As indicated (Fig. 1), the relationships between amylose content and MDMINAT, MDMAT and MDMAXAT were best fitted to a quadratic function but only 'TY4' reached significant level ($P < 0.05$ or < 0.01) to these three variables in the first-half years. In the second-half years, four tested rice cultivars showed significant relationships with these three climatic variables, the content of amylose decreased with increasing temperatures above values of 19.5, 23.5 and 28.5℃ for MDMINAT, MDMAT and MDMAXAT, respectively.

The milled grain transparency of 'TNG71', 'TK9' and 'KH145' was not significantly correlated with MDMINAT, MDMAT and MDMAXAT in the first-half years, yet 'TY4' showed a significantly negative relationship with MDMAT and MDMAXAT. When MDMINAT, MDMAT and MDMAXAT raised above 20, 23.5 and 28.5℃, grain transparency decreased (Fig. 2). That is, the extent of whiteness (chalkiness) of milled grains increased with increasing temperatures during grain-filling period in all cultivars. The changes in head rice ratio of milled grains to MDMINAT, MDMAT and MDMAXAT showed that the negative relationship existed only in 'TY4' in the first-half years, while four cultivars all had a curvilinear relationship with these three variables in the second-half years (Fig. 3). Beyond mean temperatures of 20, 24 and 29.5℃ for MDMINAT, MDMAT and MDMAXAT, respectively, head rice ratio would decrease at harvest.

As shown in the aforementioned regression analyses, climatic variables MDMINAT, MDMAT and MDMAXAT calculated from grain-filling stage were related to yield and quality of all cultivars in the second-half years, but were found only applicable to 'TY4' in the first-half years. Such a result might be partially attributed the magnitude of temperature variations during grain-filling stage in the experimental period. Data showed that temperatures varied in ranges of 1.2–1.4℃, 0.9–1.1℃, 1.0–1.2℃ and 1.2℃ in the first half and increased to 1.6–2.4℃, 1.5–2.1℃, 1.8–2.7℃ and 1.7–2.5℃ in the second half for 'TNG71', 'TK9' and 'KH145'(data not shown), respectively, so that a larger temperature regime in the second-half years was given to a higher correlation than that of the first-half years. Moreover, the self-evident results also suggested that cultivar 'TY4' bred from cooler northern region was more sensitive to warm temperature and hence, its grain quality was more negative affected by high temperatures.

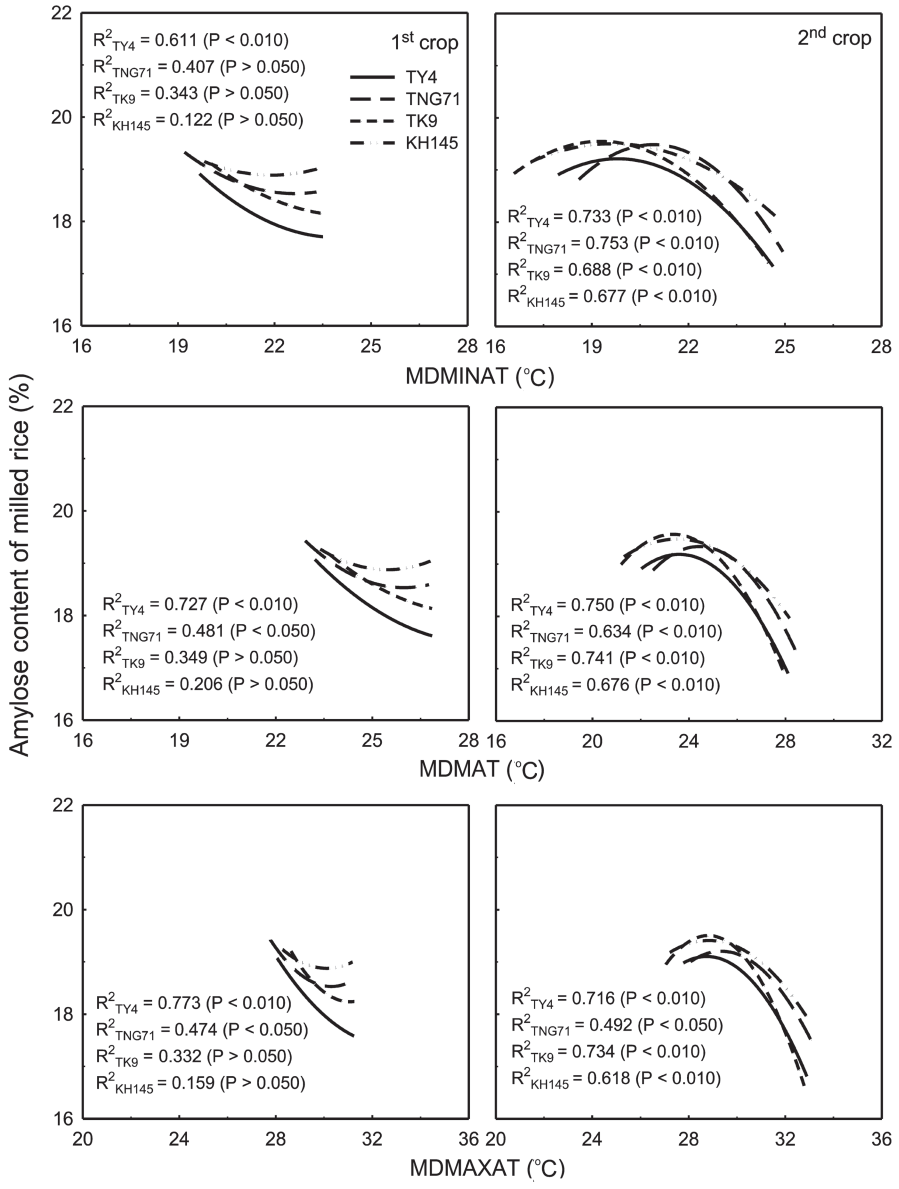

Fig. 1. Changes in amylose of milled rice to the mean values of daily minimum air temperature (MDMINAT), daily mean air temperature (MDMAT), and daily maximum air temperature (MDMAXAT) calculated from heading to harvest in the first and second crops of four rice cultivars ('TY4', 'TNG71', 'TK9', and 'KH145') grown in the cropping seasons of 2008–2010.

The distinct climatic conditions manifest in either the first or the second half of year and thus dictate a two-crop system of rice cultivation as well the differences in yield and quality of rice harvested in different crops in Taiwan (Chu & Lu 1984; Liu *et al*. 1984; Lu *et al*. 2008). As to the relationships of grain yield with MDMINAT, MDMAT and MDMAXAT of grain-filling stage, a quadratic function was fitted (Fig. 4). The relationship was significant for 'TNG71', 'TK9' and 'KH145', but not 'TY4', in the first-half years. By pooling all data col-

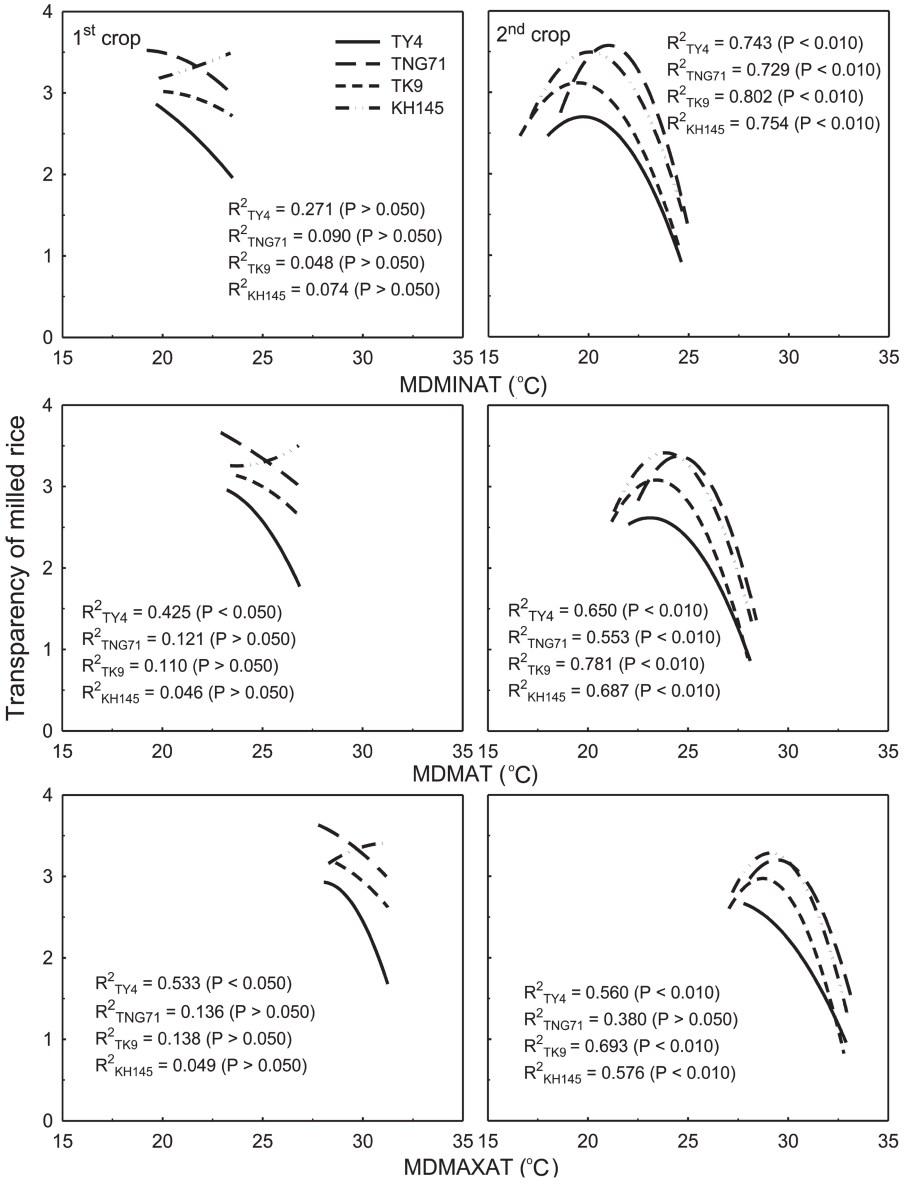

Fig. 2. Changes in transparency of milled rice to the mean values of daily minimum air temperature (MDMINAT), daily mean air temperature (MDMAT), and daily maximum air temperature (MDMAXAT) calculated from heading to harvest in the first and second crops of four rice cultivars ('TY4', 'TNG71', 'TK9', and 'KH145') grown in the cropping seasons of 2008–2010.

lected from all cultivars, the maximum yields achieved near 23, 26.5 and 31℃ for MDMINAT, MDMAT and MDMAXAT, respectively. A 2℃ increase for MDMINAT, MDMAT and MDMAXAT would cause respective 20, 18 and 16% yield decrease, implying a greater harmful effect of nighttime temperature (i.e., MDMINAT). In the second-half years, significant relationship was found in 'TY4' and 'KH145', but not in 'TNG71' and 'TK9', with MDMINAT. Again, the convex curve patterns of pooled data indicated a better temperature range for

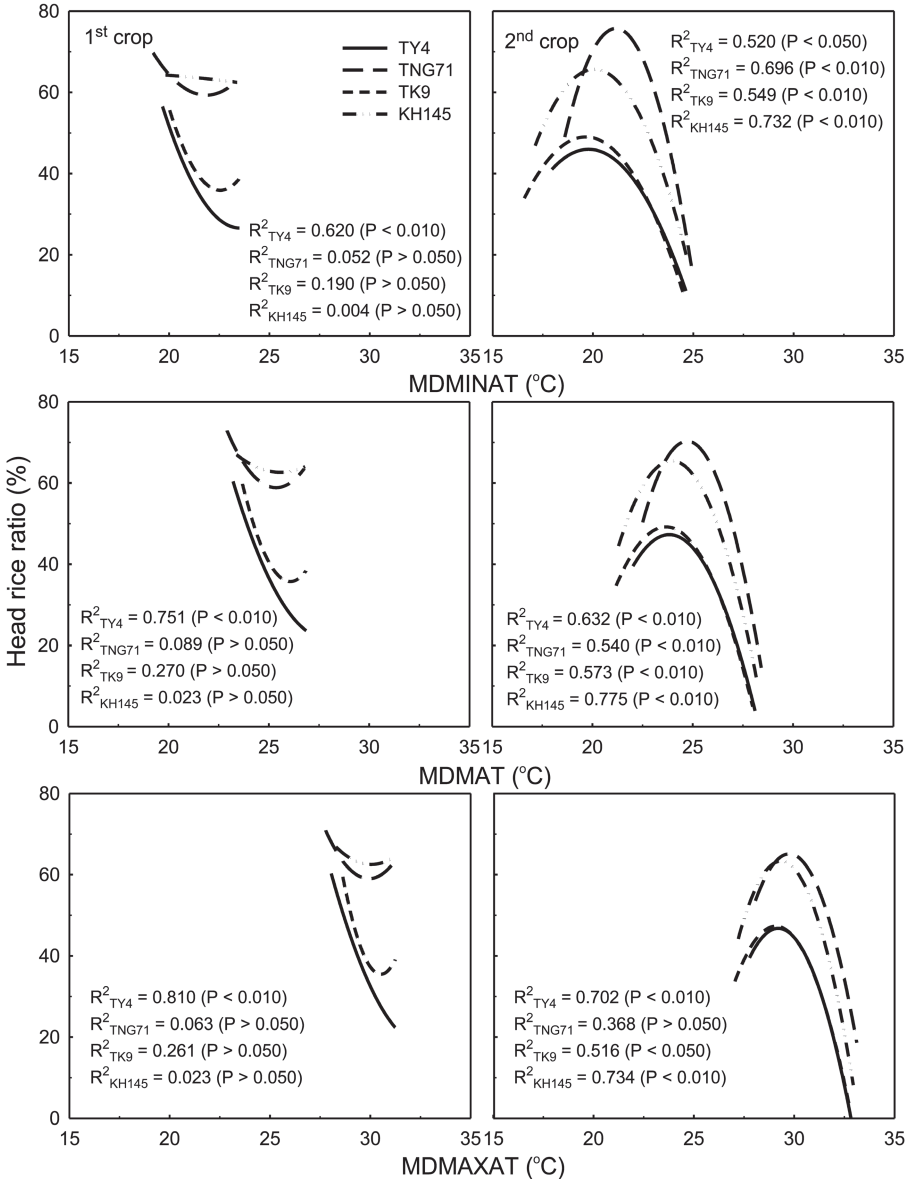

Fig. 3. Changes in head rice ratio to the mean values of daily minimum air temperature (MDMINAT), daily mean air temperature (MDMAT), and daily maximum air temperature (MDMAXAT) calculated from heading to harvest in the first and second crops of four rice cultivars ('TY4', 'TNG71', 'TK9', and 'KH145') grown in the cropping seasons of 2008–2010.

grain yield that centered near 20, 24 and 29℃ for MDMINAT, MDMAT and MDMAXAT, respectively. Temperature increases by 2℃ would result in 6, 9 and 7% drop of yield, an extent less than those of the first-half years.

Summarized from field investigations, Lur *et al*. (2006) pointed out that averaged values of daily minimum air temperature, daily mean air temperature and daily maximum air temperature lower than 22, 26 and 30℃ with daily irradiance higher than 13 MJ m^{-2} d^{-1} during grain-filling stage are a 'safe and secure

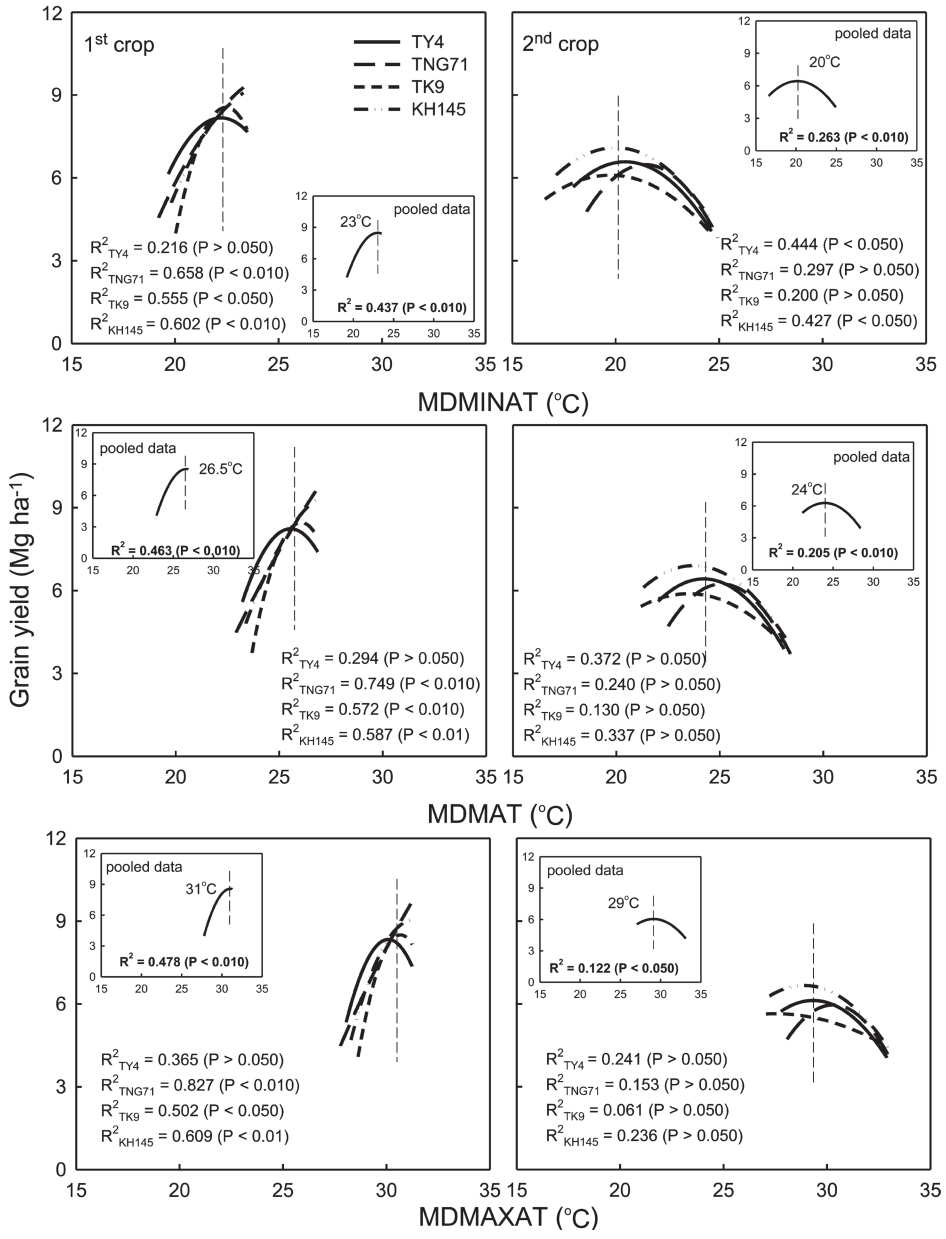

Fig. 4. Changes in grain yield of rice to the mean values of daily minimum air temperature (MDMINAT), daily mean air temperature (MDMAT), and daily maximum air temperature (MDMAXAT) calculated from heading to harvest in the first and second crops of four rice cultivars ('TY4', 'TNG71', 'TK9', and 'KH145') grown in the cropping seasons of 2008–2010.

environment' for quality rice production in Taiwan, in which conditions production of good appearance with low chalkiness grains can be high expected. This study further drew the outlines of a 'maximal yield environment' where MDMINAT, MDMAT and MDMAXAT of grain-filling stage near 23, 26.5 and 31℃ in the first-half year and 20, 24 and 29℃ in the second-half year, respectively, were the most suitable conditions for the selected rice culti-

vars to attain their maximum yield potential. Consequently, 5% variance for MDMINAT, MDMAT and MDMAXAT were computed as 22.4–23.6℃, 25.9–27.2℃ and 30.2–31.8℃ in the first-half year and 19.5–20.5℃, 23.4–24.6℃ and 28.3–29.7℃ in the second-half year to obtain 95–100% of their respective maximum yields. In other words, by adjusting planting seasons or selecting culture locations that can acquire such temperature ranges for respective cultivars, high yield of rice will be more reliable.

Both radiation and temperature are important to yield and quality of a crop. In the present research, grain yield was affected by MDNTD of grain-filling stage in the cropping seasons of the first-half years (Fig. 5), but not in the case of quality traits. However, amylose and transparency of milled grains, head rice ratio, and grain yield were significantly correlated with MDNTD in a positive curvilinear fashion in the second-half years. The increasing value of MDNTD would enhance quality traits and grain yield. The climatic variable MDIR was not significantly correlated with quality traits and grain yield in the first-half years, but influenced quality traits in the second-half years (Fig. 6). Quality traits improved with the increase of MDIR, reached the plateau, and then decreased thereafter. Nevertheless, the effects of integrated climatic factors on yield and quality of rice grains are issues worth further study and clarify, particularly to cultivars that bred from varied regions with diversified genetic contexts and environmental conditions.

Many studies reported that solar radiation and air temperature and even variation of nighttime temperature may also crucial for yield performance (Tsai *et al*. 1984; Morison 1992; Kukla & Karl 1993; Easterling *et al*. 1997; Peng *et al*. 2004; Islam &; Lee *et al*. 2009; Ho *et al*. 2012). Results from this study not only illustrated these facts but also demonstrated yield and quality of rice were fluctuated a greater extent in the second-half year than in the first-half year in Taiwan. Weather data collected in the experimental period proved a larger temperature and radiation variation in the cropping seasons of the second-half years (data not shown), which provide an unstable or even disturbed environment for growth and development of rice crops. As pointed out by Liu *et al*. (1984) that climatic factors will affect morphology and extent of expression of agronomic characters, and such phenomena vary in varieties, crops, locations and their interactions.

The prospects for future climate change and warming trend are substantial and are seemingly unavoidable and evitable based on the 2007 IPCC Fourth Assessment Report (IPCC 2007). As an example, results of this study indicated that 6–20% yield reduction would occur by 2℃ temperature increase in grain-filling stage of rice growth. To ameliorate the negative impacts on rice production and food security as a whole, strategic research plans are necessary on not just temperature but other climatic factors as well. With that, sufficient food production is feasible and applicable to meet perspectives of socio-economic consequences yielding from climate change and global warming. In addition to breeding approach for enhancing tolerance of crops to adverse environments and farming practices for improving crops adaptability (Sun *et al*. 2004; Lur *et al*. 2006; Lu *et al*. 2008), adjusting planting seasons and selecting culture locations are also proper strategies to adapt to abnormal climatic conditions in a changing climate.

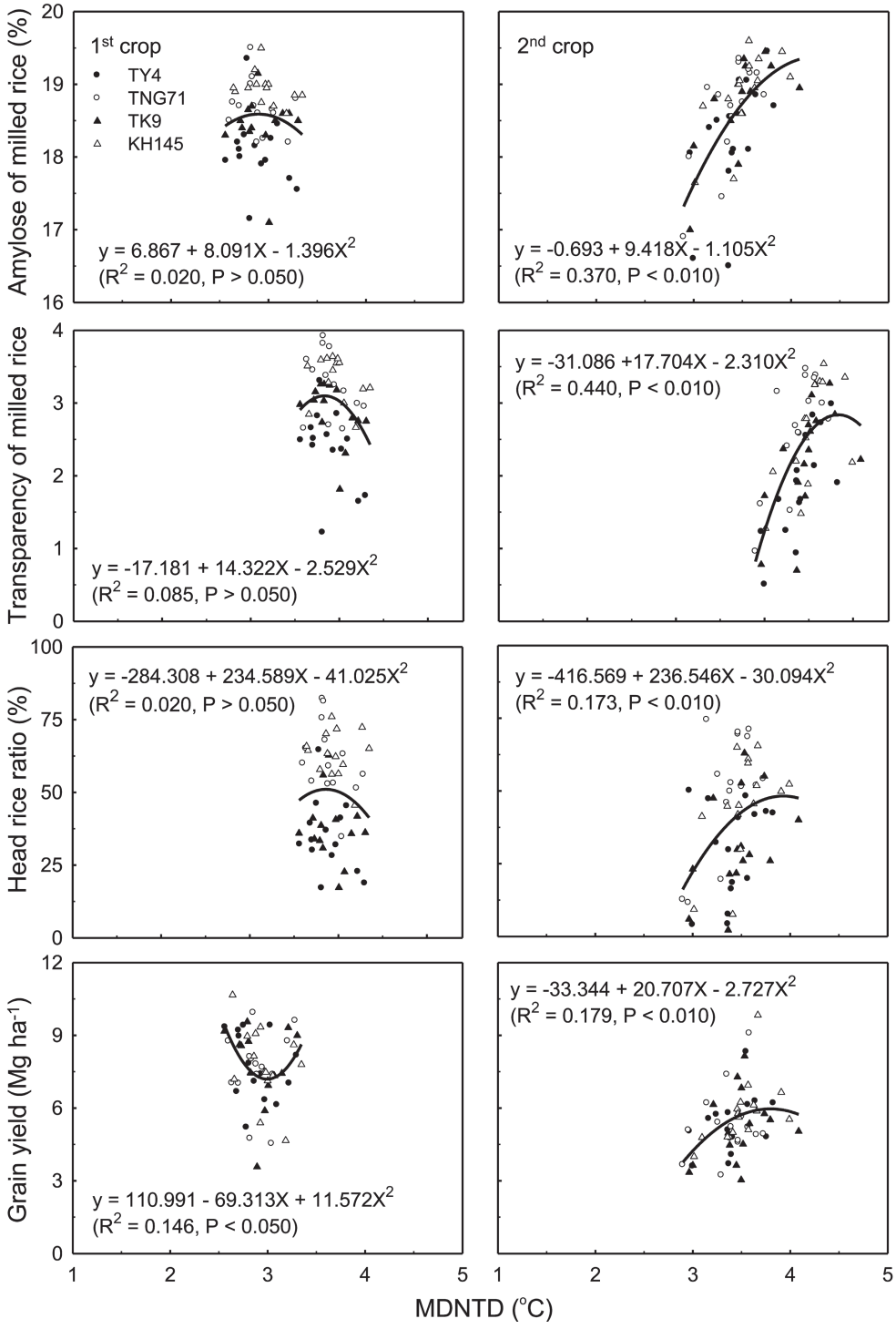

Fig. 5. Changes in amylose and transparency of milled rice, head rice ratio and grain yield to the mean values of day-night temperature difference (MDNTD) calculated from heading to harvest in the first and second crops of four rice cultivars ('TY4', 'TNG71', 'TK9', and 'KH145') grown in the cropping seasons of 2008–2010.

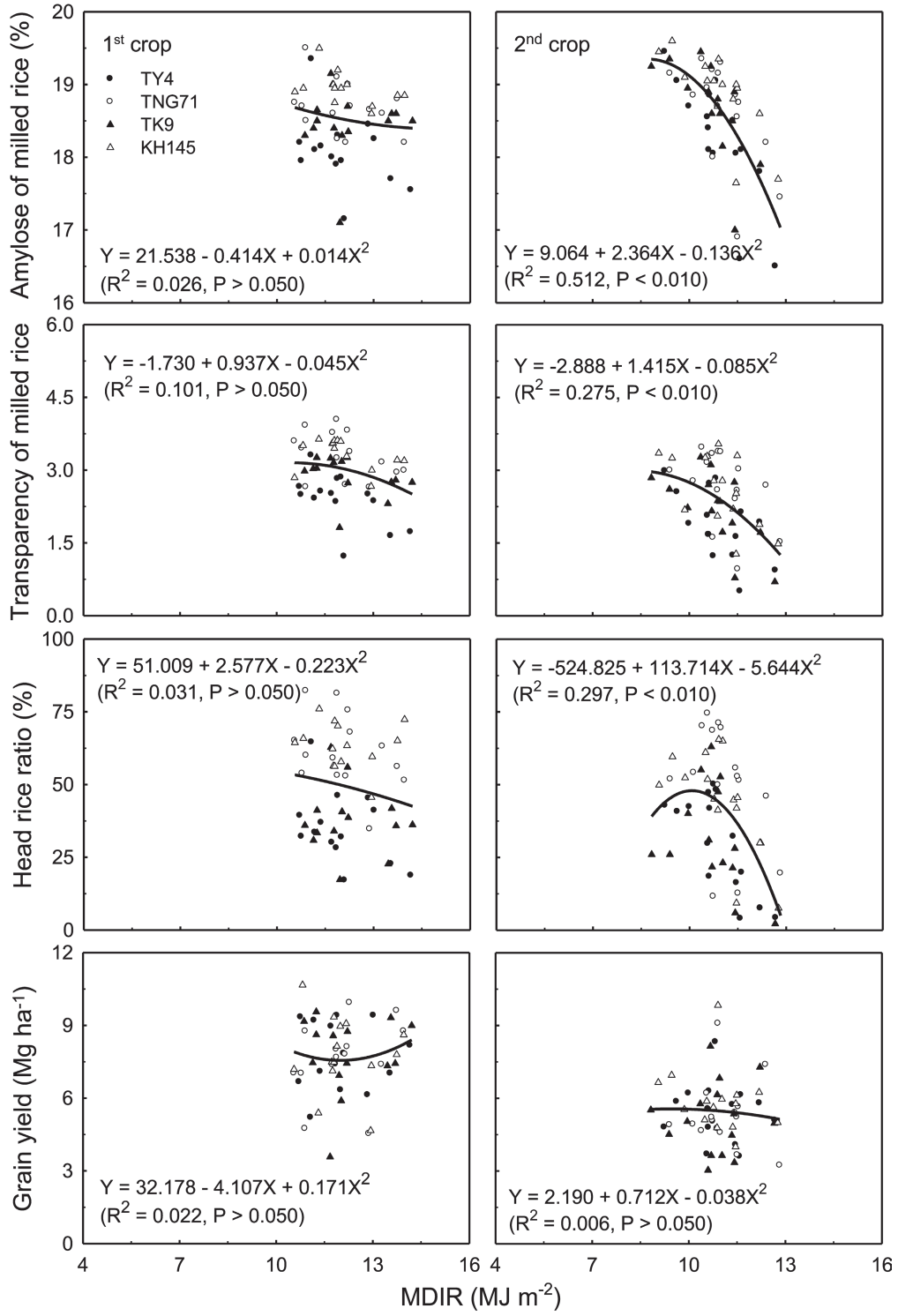

Fig. 6. Changes in amylose and transparency of milled rice, head rice ratio and grain yield to the mean values of daily irradiance (MDIR) calculated from heading to harvest in the first and second crops of four rice cultivars (‘TY4’, ‘TNG71’, ‘TK9’, and ‘KH145’) grown in the cropping seasons of 2008–2010.

REFERENCES

Ahmed, N., M. Maekawa, and I. J. Tetlow. 2008. Effects of low temperature on grain filling, amylose content, and activity of starch biosynthesis enzymes in endosperm of basmati rice. Aust. J. Agric. Res. 59:599–604.

Chen, S. E., T. T. Huang, M. H. Lin, and S. H. Cheng. 2007. Release of newly developed rice cultivar Taoyuan No.4. Res. Bullet. Taoyuan Dist. Agric. Res. Ext. Stn.. 61:1–16. (in Chinese with English abstract)

Chiu, Y. C. and C. W. Wu. 2005. Development of the new rice variety Kaohsiung 145. Res. Bull. Kaohsiung Dist. Agric. Res. Ext. Stn.. 16:1–14. (in Chinese with English abstract)

Choi, H. C. 2002. Current status and perspectives in varietal improvement of rice cultivars for high-quality and value-added products. Korean J. Crop Sci. 47:15–32.

Chu, C. and H. S. Lu. 1984. Grain-filling characteristics and its relation to yield components in the first and second rice crops. p.165–179. *in*: Regional and Seasonal Causes of Low Yield in Rice and the Measures for Improvement. (Liu, D. J. and S. C. Hsieh, eds.) Taiwan Agric Res. Inst. Special Pub. No. 16. Taichung. 322 pp. (in Chinese with English abstract)

COA, Executive Yuan. 2012. Rice. p.24–35. *in*: Agricultural Statistics Yearbook. COA Pub. Taiwan. 336 pp.

Easterling, D. R., B. Horton, P. D. Jones, T. C. Peterson, T. R. Karl, D. E. Parker, M. J. Salinger, V. Razuvayev, N. Plummer, P. Jamason, and C. K. Folland. 1997. Maximum and minimum temperature trends for the globe. Science 277:364–367.

Hirai, Y., T. Yamadu and M. Tsuda. 2003. Effects of temperature at ripening period on dark respipercentage and dry matter production in rice–Comparison of the effects in the plants sown in pot at different times. Jpn. J. Crop Sci. 72:436–442. (in Japanese with English abstract)

Ho, C. H., C. M. Yang, C. L. Hsiao, and M. H. Lai. 2012. Effect of climatic conditions during heading to harvest stage on quality of rice cultivar TNG 71. J. Taiwan Agric. Res. 61:222–240. (in Chinese with English abstract)

Hong, M. C., A. N. Hsu, and C. F. Li. 2000. Analysis of rice quality. p.252–266. *in*: Annual Report of Rice Improvement 2000. Taichung Dist. Agric. Res. Improve. Stn.. Changhua. 350 pp. (in Chinese)

Hsu, C. S. and H. Sung. 1993. Development of new rice variety: Tai-Keng 9. Harvest Farm Magazine 43:14–20.

Hsu, C. S., K. C. Lu, P. C. Wu, and K. C. Lin. 2000. Study on cultivation practices to improve rice quality. p.162–168. *in*: Annual Report of Rice Improvement 2000. Taichung Dist. Agric. Res. Improve. Stn.. Changhua. 350 pp. (in Chinese)

Huang, J. J. and H. S. Lur. 2000. Influences of temperature during grain filling stages on grain quality in rice (*Oryza sativa* L.) 1. Effects of temperature on yield components, milling quality, and grain physico-chemical properties. J. Agric. Assoc. China 1:370–389. (in Chinese with English abstract)

IPCC. 2007. Summary for policymakers. In: climate change 2007: The physical science basis. p.1–18. *in*: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds.) Cambridge University Press. Cambridge. 996 pp.

Islam, M. S. and J. I. L. Morison. 1992. Influence of solar radiation and temperature on irrigated rice grain yield in Bangladesh. Field Crops Res. 30:13–28.

Kim, K. H., S. Y. Cho, H. P. Moon, and H. C. Choi. 1994. Breeding strategy for improvement and diversification of grain quality in rice. Korean J. Breed. 26:1–15.

Kim, J., J. Shon, C. K. Lee, W. Yang, Y. Yoon, W. H. Yang, Y. G. Kim, and B. W. Lee. 2011. Relationship between grain filling duration and leaf senescence of temperate rice under high temperature. Field Crops Res. 122:207–213.

Kukla, G. and T. R. Karl. 1993. Nighttime warming and the greenhouse effect. Environ. Sci. Technol. 27:1468–1474.

Lai, M. H., C. P. Li, C. S. Tseng, H. J. Huang, C. G. Chern, and Y. C. Kuo. 2001. Development of aromatic rice variety Tainung 71 (Yihchuan aromatic rice). J. Agric. Res. China 50:1–11. (in Chinese with English abstract)

Lee, Y. J., C. M. Yang, and C. H. Hsiao. 2009. Influence of climatic conditions on production of rice cultivar TNG 71. J. Taiwan Agric. Res. 58:45–54. (in Chinese with English abstract)

Lin, A. C., L. K. Lai, and L. F. Lee. 1979. Studies on the cause of low yielding in the second crop of rice plant. IV. Comparison of the characteristics of heading and ripening process between the first and second crops of rice plant. J. Agric. Assoc. China 107:17–24. (in Chinese with English abstract)

Lin, A. C. and L. M. Hung. 1979. Studies on the cause

of low yielding in the second crop of rice plant. VI. Effect of temperature and light intensity on heading and ripening of rice plant. J. Agric. Assoc. China 108:24–38. (in Chinese with English abstract)

Liu, C., S. C. Hsieh, and M. H. Lin. 1984. Influence of climate on the yield and agronomic characters of the first and second crop rice in Taiwan. p.59–72. in: Regional and Seasonal Causes of Low Yield in Rice and the Measures for Improvement. (Liu, D. J. and S. C. Hsieh, eds.) Taiwan Agric Res. Inst. Special Pub. No. 16. Taichung. 322 pp. (in Chinese with English abstract)

Liu, D. J. and S. C. Hsieh. 1984. Regional and Seasonal Causes of Low Yield in Rice and Measures of Improvement. Taiwan Agric Res. Inst. Special Pub. No. 16, Taichung. 322 pp. (in Chinese with English abstract)

Lu, M. M., Y. L. Chen, and G. H. Chen. 2008. Impact of global warming trend on rice cultural environment in Taiwan. Crop Environ. Bioinformat. 5:60–72. (in Chinese with English abstract)

Lur, H. S., C. L. Hsu, C. W. Wu, C. Y. Lee, C. L. Lao, Y. C. Wu, S. J. Chang, C. Y. Wang, and M. Kondo. 2009. Changes in temperature, cultivation timing and grain quality of rice in Taiwan in recent years. Crop Environ. Bioinformat. 6:175–182.

Lur, H. S., Y. H. Liu, and Agrometeorology Section of Central Weather Bureau. 2006. Environmental challenge and strategy for quality rice culture in Taiwan. Crop Environ. Bioinformat. 3:297–306. (in Chinese with English abstract)

Mohammed, A. R. and L. Tarpley. 2010. Effects of high night temperature and spikelet position on yield-related parameters of rice (*Oryza sativa* L.) plants. Eur. J. Agron. 33:117–123.

Morita, S., H. Shiratsuchi, J. Takanashi, and K. Fujita. 2004. Effect of high temperature on grain ripening in rice plants.: Analysis of the effects of high night and high day temperatures applied to the panicle and other parts of the plant. Jpn. J. Crop Sci. 73:77–83. (in Japanese with English abstract)

Nagarajan, S., S. V. K. Jagadish, A. S. H. Prasad, A. K. Thomar, A. Anand, M. Pal, and P. K. Agarwal. 2010. Local climate affects growth, yield and grain quality of aromatic and non-aromatic rice in northwestern India. Agric. Ecosyst. Environ. 138:274–281.

Peng, S., J. Huang, J. E. Sheehy, R. C. Laza, R. M. Visperas, X. Zhong, G. S. Centeno, G. S. Khush, and K. G. Cassman. 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. 101:9971–9975

Sun, T. S., H. Yua, and C. N. Sun. 2004. Courses and prevention methods of chalky and defective rice grain formation. China Rice 1:43–45. (in Chinese)

Tsai, J. C., M. C. Shen, C. S. Chen, and D. J. Lin. 1984. Effect of shading on the heading date, nutrient concentrations, dry matter production and yield of rice varieties. p.83–98. *in*: Regional and Seasonal Causes of Low Yield in Rice and the Measures for Improvement. (Liu, D. J. and S. C. Hsieh, eds.) Taiwan Agric Res. Inst. Special Pub. No. 16. Taichung. 322 pp. (in Chinese with English abstract)

Yamakawa, H., T. Hirose, M. Kuroda, and T. Yamaguchi. 2007. Comprehensive expression profiling of rice grain filling-related genes under high temperature using DNA microarray. Plant Physiol. 144:258–277.

Yang, C. M. 1994. Response of rice yield in relation to solar radiation and air temperature under soil water deficits. Chinese J. Agromet. 1:27–34.

Zakaria, S., T. Matsuda, S. Tajima, and Y. Nitta. 2002. Effect of high temperature at ripening stage on the reserve accumulation in seed in some rice cultivars. Plant Prod. Sci. 5:160–168.

穀粒充實期間氣象因子對台灣不同地區選育稻種之米質與產量影響

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摘要

何佳勳、楊純明、蕭巧玲、賴明信。2013。穀粒充實期間氣象因子對台灣不同地區選育稻種之米質與產量影響。台灣農業研究 62(4):321–339。

由抽穗至收穫之穀粒充實期間氣象環境變化將影響稻米品質與產量，惟對選育自不同氣象環境的稻種將存在品種間差異性，探討與釐清這些差別效應將有助於建立各別地區性策略，以有效因應氣候變遷並穩定地區稻米供給而維護糧食安全。本研究於 2008–2010 年在行政院農業委員會農業試驗所農場 (台中市霧峰區) 進行三年期間上、下半年稻作之節氣栽植，三年總計 29 個栽植期。每個栽植期皆以 4 個良質稻種為試材，由北往南包括 '桃園 4 號' ('TY4')、'台農 71 號' ('TNG71')、'台粳 9 號' ('TK9') 及 '高雄 145 號' ('KH145') 等。試驗期間收集試區一級農業氣象測站之氣象測值，計算各稻種各栽植期自抽穗至收穫的穀粒充實期所量測的日均溫、日最高溫、日最低溫、日夜溫差、日照時數與日射量等六項氣象因子測值之平均值 (即 MDMAT、MDMAXAT、MDMINAT、MDNTD、MDSH、MDIR)，以分析六個氣象變因對不同稻種米質性狀與產量之差異影響。由回歸分析顯示，4 個良質稻種米質性狀受到穀粒充實期溫度變因 (MDMINAT、MDMAT 及 MDMAXAT) 影響，升溫將造成白米直鏈性澱粉、透明度及完整米率逐漸下降趨勢，惟上半年以 'TY4' 達顯著水準，下半年則 4 個稻種皆呈現顯著二次曲線關係。又產量與溫度變因之間為二次凸形曲線關係，各稻種有其產量表現之最佳平均值。總合 4 稻種資料，歸納出上半年栽植期之穀粒充實期最佳 MDMINAT 為 23℃、MDMAT 為 26.5℃、MDMAXAT 為 31℃時可獲得最大產量，而下半年則分別為 MDMINAT 20℃、MDMAT 24℃、MDMAXAT 29℃。另發現下半年各栽植期米質性狀與 MDNTD、MDIR 均呈現極顯著二次曲線關係，而穀粒產量則與 MDNTD 呈現極顯著二次回歸相關。綜此顯見不同稻種於穀粒充實期間，氣象環境的改變將影響米粒化學組成、物理特性及產量，而各米質性狀各有其不同之主要影響氣象變因與權重，且溫度上升超過最佳門檻值之後將下降。因此，為穩定稻米品質與產量，勢必篩檢合適栽植地區或栽植期以調適栽植期的氣象環境變化及未來變遷趨勢，尤其在氣候快速變遷情境下更需彈性因應。

關鍵詞：穀粒充實期間、氣象變因、不同地區選育稻種、米質、產量。

投稿日期：2013 年 8 月 26 日；接受日期：2013 年 11 月 7 日。
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